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COMPARISON OF SPHERICAL AND ELLIPSOIDAL FORM FUNCTIONS FOR EVALUATING BLACK POWDER

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Previous reported experimental closed-bomb data have been re-evaluated by including both the actual particle size distribution in models that consider the grains first as spheres, and then as ellipsoids. Small but significant improvements are demonstrated by applying more realistic physical parameters; however, computed results are far removed from strand burn rate measurements and the conclusion offered is that continued investigation suggests that grain fracture or grain break-up dominate closed-bomb evaluation techniques.

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I. INTRODUCTION

Black powder has been a subject of study for this and other laboratories for some extended period of time. Throughout our work at the Ballistic Research Laboratory we have concentrated our studies to particular lots of black powder and its ingredients from GOEX, Du Pont and Indiana. Our recent report "Evaluation of Black Powder Produced by Indiana Army Ammunition Plant"[1] contains closed-bomb evaluation of GOEX 75-44 black powder as well as its size distribution. Further, the output of the thermal code "BLAKE" was provided by Eli Freedman of the BRL considering the chemical composition of charcoal and black powder. With these data the closed-bomb experiments were evaluated in 1984 by a BRL program[2] called CBRED2.

These early computations considered black powder grains as spheres having but one average radius and the program resulted in a burn rate equation that did not agree with experimentally determined strand burn rates. Computer sensitivity analysis showed that changing the value of the chosen radius affected the burn rate coefficient more than exponential factor. The conclusion offered in that report was: "closed-bomb burning rate equations have larger exponents than are derived from strand burning rates and it was proposed that the larger exponents embraced both combustion and grain break-up or non-uniform ignition. In contrast, precision of the strand burn rates is good and reflects an uncomplicated and defined mode of combustion i.e., that of a "cigarette burn." Such values could be used to provide a more precise ranking of black powder performance." The problem is the lack of a data base.

The advent of a recently polished and documented BRL computer program IBHVG2, which stands for "Interior Ballistics of High Velocity Guns",[3] affords the opportunity of including up to five separated propellant inputs that were used to represent five different grain sizes. Also of importance, was the kindness of the authors to modify this program to include the shape of an ellipse of rotation. We applied this program to the data at hand and, in effect, extended the scope of the previous work. The closed-bomb situation was implemented by citing a much too heavy shell, 50 lbs., and imparted a frictional resistance that exceeded the maximum anticipated pressure. Although we intend to have this report stand on its own, it would be advisable to read them in sequence. One drawback is that the program IBHVG2 does not output a burn rate equation but the program uses such an equation as input to calculate pressure and surface area histories.

II. APPROACH

As one inspects the shape of class 1 black powder it is apparent that the grains are of non-uniform character and that they are far from the spherical form normally assumed in various calculations. It was thought that an ellipse of rotation might be a better estimate of the geometry and from several measurements the long radius, a, was judged to be in a 4:3 ratio to the two equal radii, b. Equations for volume and surface area were added to the computer program and to form a laminar burn the radii were decreased by an equal increment. Early computations showed that the volume decreased to zero before the surface area and an inadequacy of one percent was noted throughout the burning history. The problem is that computations estimate the laminar burn distance from the burn rate equation whereas the surface area and volume are

calculated from the geometry. For the spherical case these are exact solutions thus volume and surface area agree; however, in the elliptical model even though both radii decrease by the same amount the curved shoulder is slightly bigger. This means that in a laminar burn of some distance, x, the new shape is not strictly an ellipsoid and thus the calculation is an approximation. A correction factor of one percent was added to the program and this adjustment allows the program to solve the form function equations to estimate both the intermediate and final closed-bomb conditions. This correction applies just to the case considered where the axes radii are in the ratio of 4:3. As will be discussed later, the total pressure calculated from the spherical case is an exact solution which differs from the elliptical case by much less than one percent giving the authors confidence in the treatment of this model. The volume and surface area equations are given below:

$$V = 4/3 \, \Pi \, ab^2 \tag{1}$$

$$SA = 2\Pi b^2 + \frac{2\Pi ab \, \sin^{-1} e}{e} \qquad \text{Where } ae = \sqrt{a^2-b^2} \tag{2}$$

The calculations require thermodynamic and physical property data and all of the required input information was extracted from a former report[1] and is given in Table 1. In addition, the pressure history is included. The input to the thermodynamic code BLAKE requires the chemical composition of the propellant and in the case of black powder the codes require the composition of charcoal[4] as well as the other ingredients. Eli Freedman[5] performed such calculations for the GOEX samples evaluated in his and this report. For the first time charcoal has been represented by its elemental composition as opposed to only carbon as had been the custom. For the GOEX samples Freedman used the chemical composition of charcoal given by Rose[6] as "Roseville B" made by the Roseville Charcoal Co. of Zanesville, OH, and the potassium nitrate/sulfur/charcoal concentrations were taken from the data sheets supplied by Indiana.

Since the closed-bomb data and particle size distribution are crucial to the present evaluation a description of these experiments, taken from Reference 1 follows.

III. EXPERIMENTAL

A. Grain-Size Distribution

Class-one black powder consists of grains that pass through a number four sieve (4.75 mm) and not a number eight sieve (2.36 mm). One hundred grams of black powder was placed on a stack of sieves, four through eight, and the assembly was shaken. The portion held by each sieve was weighed.

B. Density

The bulk density of black powder is normally given as the ratio of its weight divided by its volume as measured by the amount of mercury displaced by the sample.

Table 1. Class 1 GOEX 75-44 Black Powder

Size and Weight Distribution

Sieve #	>4	5	6	7	8	<8	Total
Largest Opening (in)	0.187	0.157	0.132	0.110	0.0929		
Weight (%)	0.31*	9.49	26.69	22.25	28.46	11.70	98.89
Weight (lbs)		0.003000	0.007489	0.06194	0.007923	0.003257	0.02784
Mean Diam (in)**		0.172	0.144	0.121	0.0985	0.0929	
Long Diam (in)		0.229	0.192	0.161	0.131	0.124	

Global Values

Force, Impetus	Burning Rate Equation**		Flame Temperature
$Ft\text{-}lb_F/lb_m$	Alpha	Beta	°K
95583	0.164	0.436	2038

Density	Co-Volume	Chamber Volume	Gamma
lb/in^3	in^3/lb	in^3	---
0.06367	27.67	5.40	1.269

Experimental Pressure-Time Data

Time ms	Pressure psi	Time ms	Pressure psi	Time ms	Pressure psi	Time ms	Pressure psi
0	35	7	363	14	3596	21	6398
1	45	8	505	15	4269	22	6504
2	61	9	720	16	4860	23	6575
3	82	10	1066	17	5252	24	6623
4	116	11	1565	18	5739		
5	170	12	2189	19	6032		
6	251	13	2885	20	6245		

---

*0.31 added to 9.49

**Mean diameter for spheres and minor axis of ellipsoid in a particular size interval. Long diameter is the length of the long ellipsoid axis.

***Burn rate, Br, in in/s and pressure, p, in psi then: Br = Beta P^{alpha}

C. Closed-Bomb Evaluation

Closed-chamber experiments were performed in a Technoproducts Impulse Bomb which has an internal volume of 88.5 cubic centimeters. Class-one black powder was evaluated at a loading density of 0.14 gram per cubic centimeter. To achieve a better degree of reproducibility, the charges were placed in Dacron bags with an Atlas M100 electric match inserted in the center of the charge. Pressure was measured with a Kistler 607C3 pressure transducer and Kistler 504E charge amplifier. Data were acquired and recorded using a Nicolet Explorer III digital oscilloscope.

D. Strand Burn Rates

One of the combustion tests invoked was to grind grains of black powder such that it passed through a 120 mesh screen. This material was pressed into sticks which were dried, burned, and photographed using high-speed movie techniques.[7] Burning rates were determined from the slope of the position history of the burning interface plotted as a function of time. From previous work the regression error of estimate is about two percent. This burning rate equation is given in Table 1 and was used as input to the IBHVG2 computer program to represent the rate of combustion.

IV. RESULTS

The surface area produced by each of five particle sizes and the number of grains in each size is given first for the spherical assumption in Figure 1 and secondly for the elliptical size distribution in Figure 2. The surface area values in these five graphs are summed and the resulting total surface area using five radii are compared, in Figures 3 and 4, to the calculation where one average radius or set of radii represents the entire sample.

In Figure 5 the pressure histories resulting from the spherical and elliptical calculations using a five part particle size distribution are compared to experimental data.

V. DISCUSSION

Surface area, at particular times, is directly proportional to the amount of gas produced. Surface area of each of the five particle sizes for the spherical and ellipsoid cases are given in Figures 1 and 2, and both these graphs show real but small differences. The effect of modeling a particle size distribution as contrasted to assuming an average radius or radii becomes clear in Figures 3a and 4a where the total surface areas of both models are compared. In curves 3b and 4b the ratio of these curves show rather large differences at both early and late times and it is clear that using the particle size distribution gives a better representation of the facts, at least in the case studied here. The situation could be more extreme in a particularly skewed distribution but little data has been reported for class one distributions by manufacturers thus generalizations can not be made. Large differences have been noted by four manufacturers of black powder, suggesting that this parameter should be evaluated before serious work is attempted.

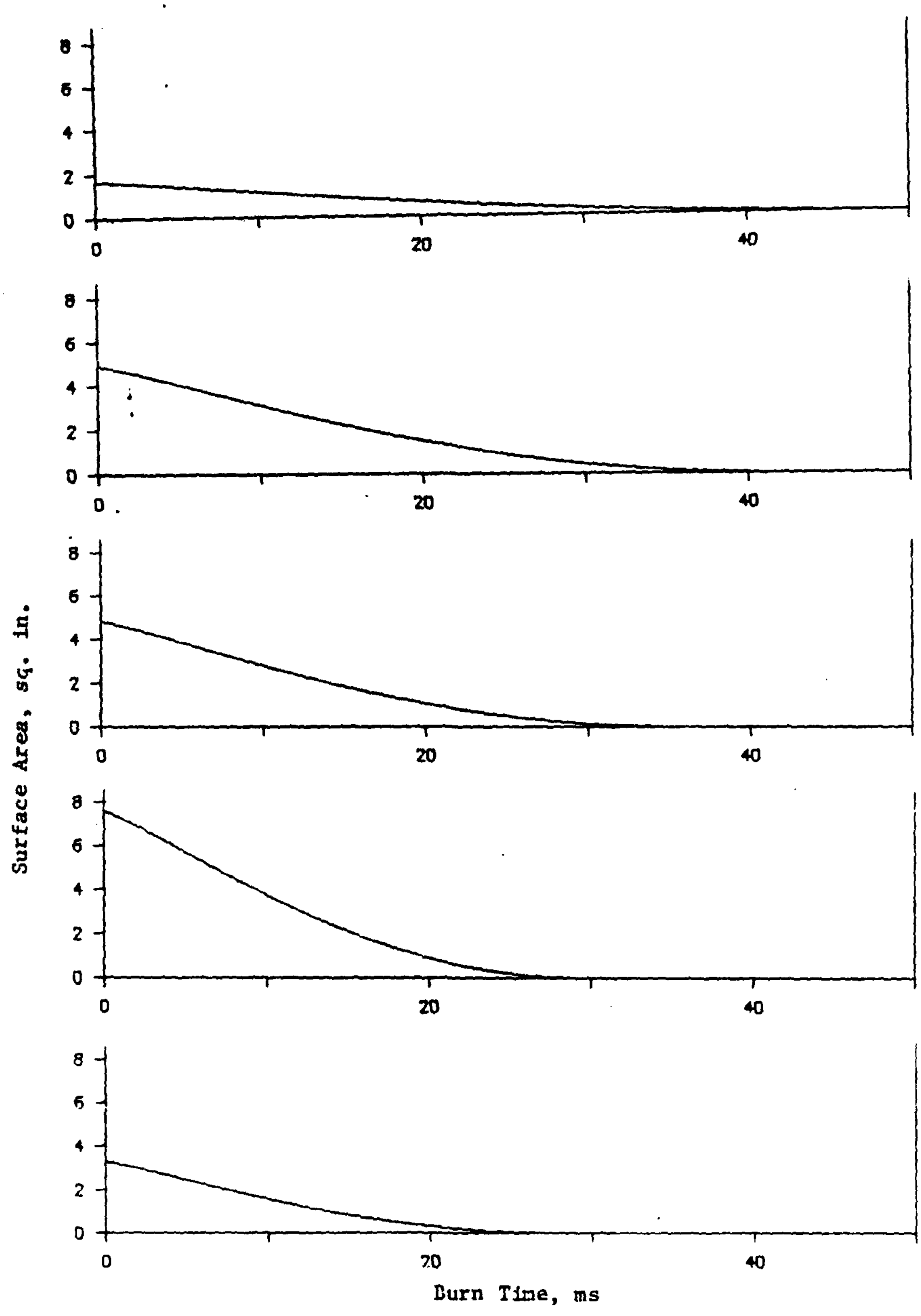

Figure 1. Surface Area of Five Spheres as a Function of Burning Time, In Descending Order, Where Largest Radius is Upper Curve.

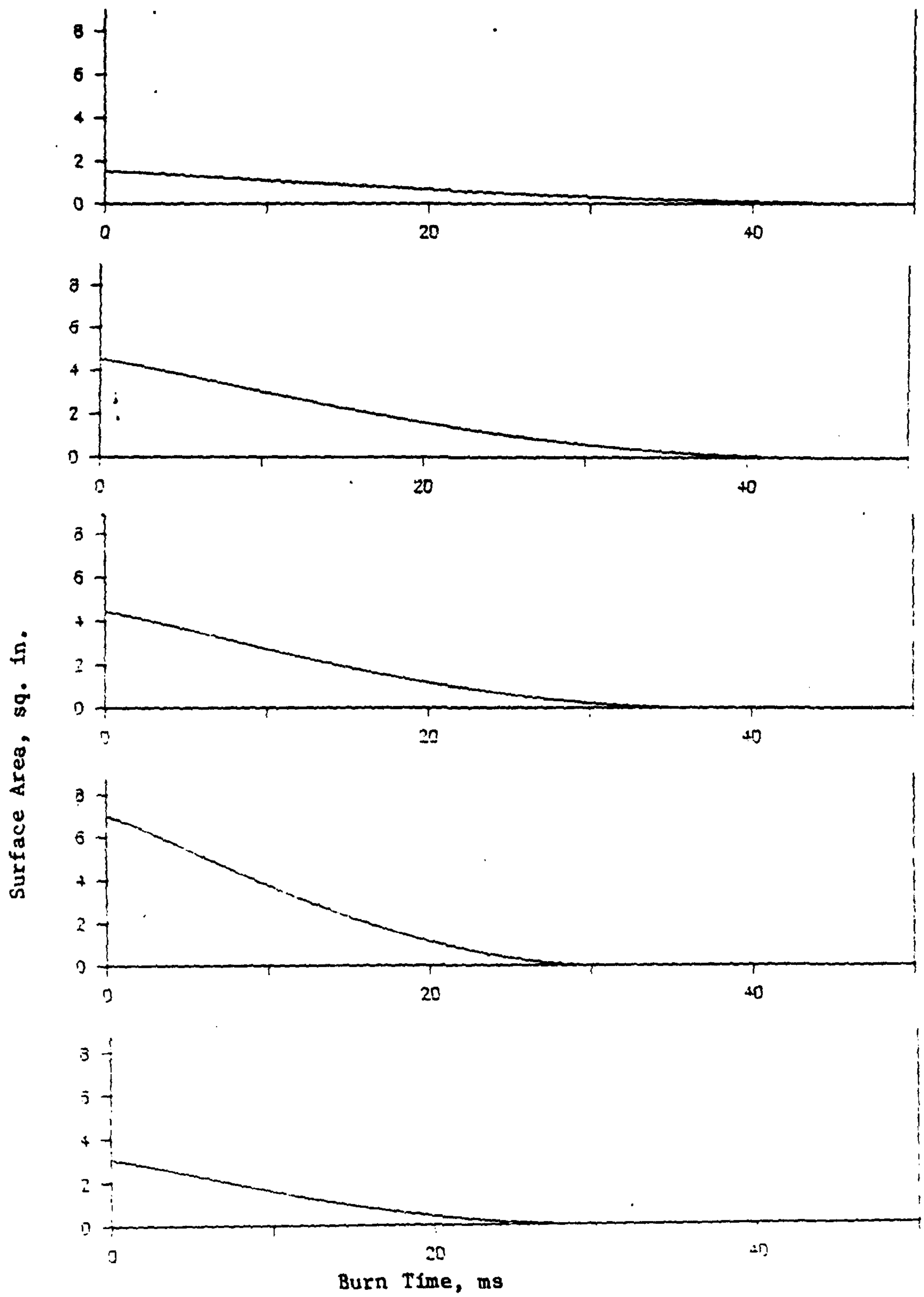

Figure 2. Surface Area of Five Ellipsoids as a Function of Burning Time, In Descending Order, Where Largest Radii is Upper Curve.

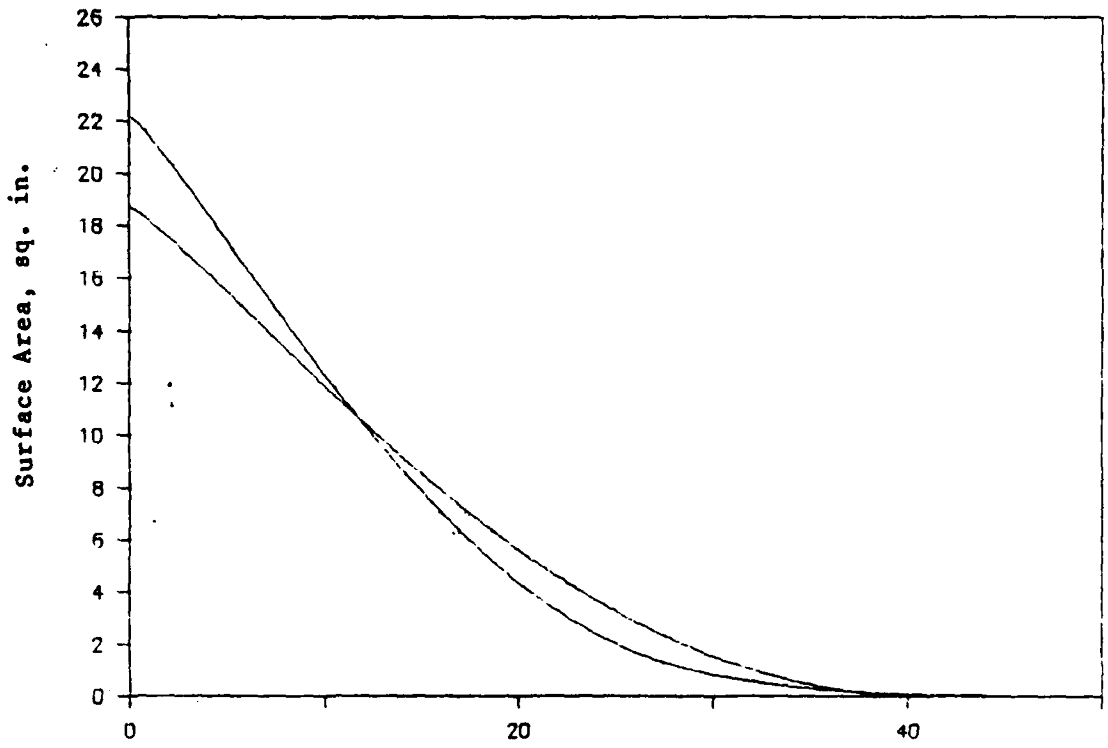

Figure 3a. Total Surface Area of Five Spheres (upper Curve, Left) to Surface Area of One Sphere of Average Radius Shown as a Function of Burning Time

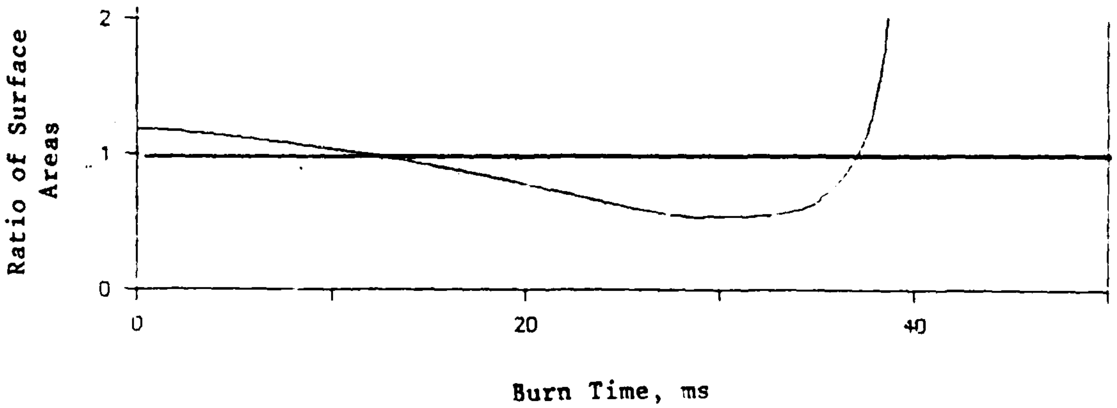

Figure 3b. Ratio of Curves 3a as a Function of Burning Time

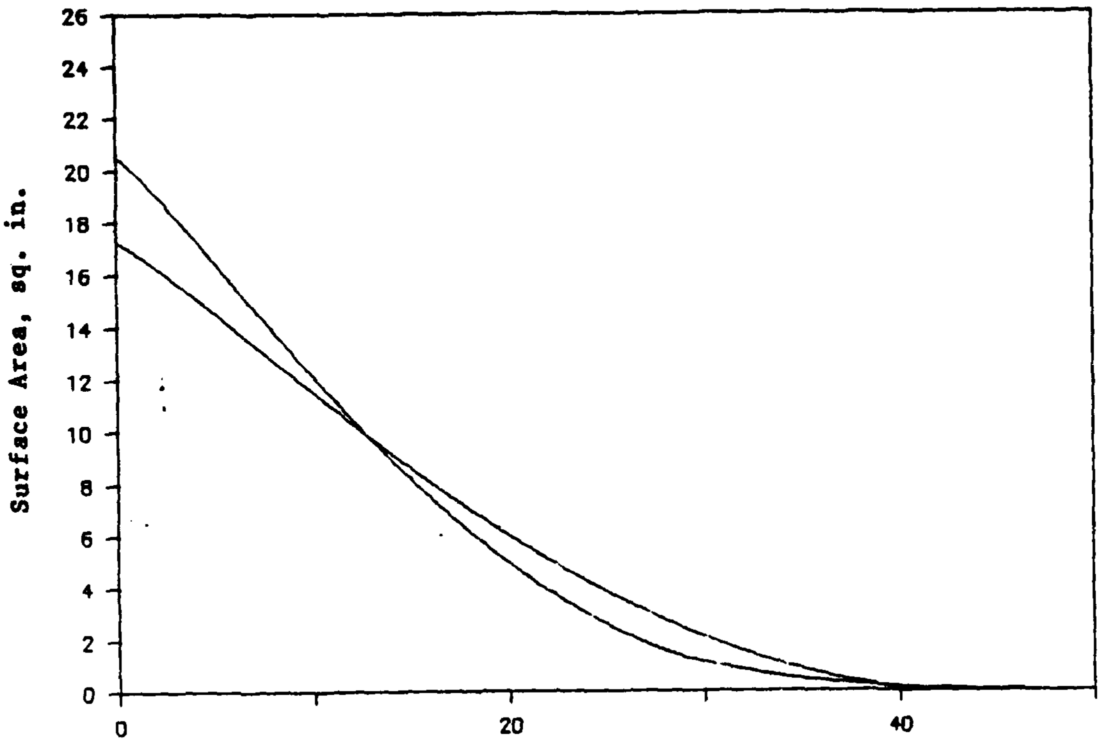

Figure 4a. Total Surface Area of Five Ellipsoids (Upper Curve, Left) to Surface Area of One Ellipsoid of Average Radius Shown as a Function of Burning Time

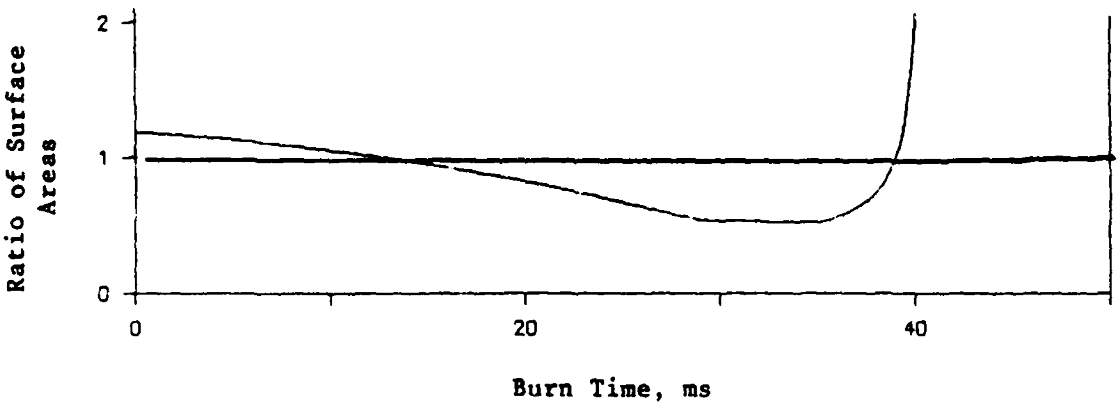

Figure 4b. Ratio of Curves 4a as a Function of Burning Time

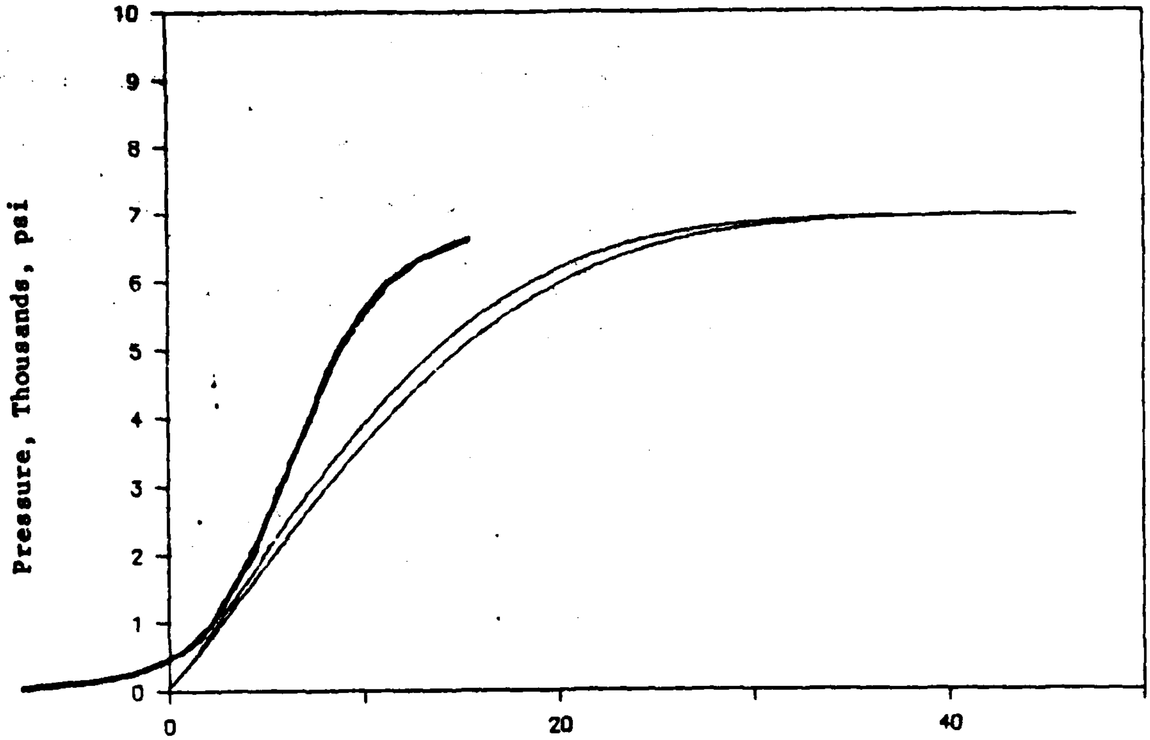

Figure 5a. Pressure as Function of Burning Time. Upper Curve - GOEX 75-44 Experimental Data, Middle Curve - Calculated Response of Five Spheres, and Lower Curve - Calculated Response of Five Ellipsoids

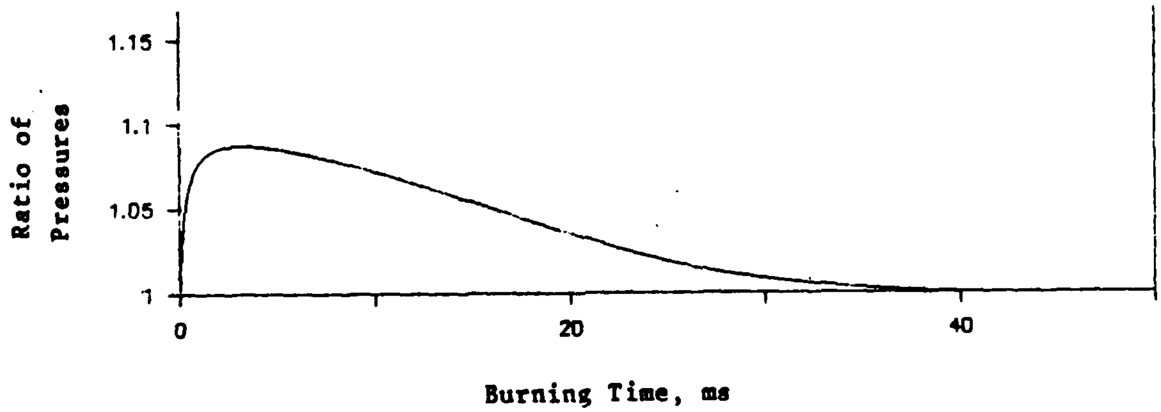

Figure 5b. Ratio of Curves 5a, Calculated Data, as a Function of Burning Time

Since the curves in Figures 1-4 are so similar, Table 2 was prepared where the various surface areas have been listed at zero time as well as the maximum pressure produced. From this table it is seen that by considering the particle size distributions for both models, the initial surface area increases by 19 percent and the ellipsoid, if constituting a better modeling of the facts, reduces this surface area by 8.5 percent. The calculated maximum pressure of the spherical and ellipsoid forms differ by 6 parts in 10,000 which is a measure of the precision of the correction made in the program. One other interesting fact is that the thermal BLAKE evaluation made by E. Freedman predicts the maximum pressure in the closed-bomb to be 6940 psi, a value that is independent of all geometry and is in reasonable agreement with the estimates in Table 2.

Table 2. Surface Area and Pressure Relationships

	Surface Area at Zero Time	Maximum Pressure
Sphere (Average Radius)	18.739	6952
Sphere (r=1-5)	22.252	6956
Sphere (r=1)	1.6436	
(r=2)	4.9009	
(r=3)	4.8239	
(r=4)	7.5800	
(r=5)	3.3038	
Ellipsoid (Average Radii)	17.258	6960
Ellipsoid ($r_a r_b$ = 1-5)	20.508	6961
($r_a r_b$ = 1)	1.5149	
($r_a r_b$ = 2)	4.5154	
($r_a r_b$ = 3)	4.4467	
($r_a r_b$ = 4)	6.9880	
($r_a r_b$ = 5)	3.0432	

VI. CONCLUSIONS

It would appear that significant improvements have been achieved in evaluation techniques where the model presented is a better representation of class one black powder. However, when the best pressure estimates of this work are compared to experimental data in Figure 5, it is seen that the calculations yield pressure histories that are too small. This result is taken as further evidence that closed-bomb experiments reflect either a grain fracture mode or a grain break-up process that is not included in our modeling.

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